Superconducting RF for the Facility for Rare Isotope Beams

W. Hartung

CLASSE Seminar
Cornell University, 3 August 2010
Outline

- Introduction: FRIB Overview
- FRIB Science
- FRIB Layout
  - Linac
  - Beam Delivery
- FRIB Resonators
- Systems Testing
- Bandwidth, RF power, RF couplers
- FRIB Cryomodules
- Summary
Introduction: FRIB Overview
Facility for Rare Isotope Beams
Historical Background

1999 ISOL Task Force report proposes Rare Isotope Accelerator (RIA)
  • Based on 400 MeV/u 100 kW heavy-ion linac

2003 RIA ranks 3rd in DOE 20-year Science Facility Plan

2006 Rare Isotope Science Assessment Committee (RISAC) of the Academies endorses construction of FRIB
  • Based on less expensive 200 MeV/u 400 kW heavy-ion linac

2007 Nuclear Science Advisory Committee (NSAC) makes construction of FRIB the second highest priority for nuclear science

2008 DOE issues a Funding Opportunity Announcement (FOA) for FRIB (20 May – application due 21 July) and conducts merit review and evaluation of proposals

2008 DOE selects MSU application (11 December)
Cooperative Agreement signed June 2009 (DOE contract with MSU)

Current Activities
- R&D
  - Superconducting resonators
  - Ion charge stripping (Argonne, RIKEN, MSU)
  - Radiation-resistant magnets (Brookhaven, MSU)
  - Gas stopping
  - High-power target
  - High-power beam dumps
- Conceptual Design
- Environmental Assessment
- Reaccelerator fabrication (ReA3, funded by MSU)

Milestones
- CD-1 (approve alternative selection and cost range) Summer 2010
- CD-2, CD-3
- CD-4 (project complete) ~2019 (subject to funding profile)
### FRIB: Cultural Impact

<table>
<thead>
<tr>
<th>You Tube Videos</th>
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</tr>
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<tr>
<td>CERN “Large Hadron Rap”</td>
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Katherine McAlpine  
2007 graduate of MSU  
aka “alpinekat”

as of 2 August 2010
## FRIB: Cultural Impact

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*as of 2 August 2010*

![Image of Katherine McAlpine](image)

Katherine McAlpine
2007 graduate of MSU
aka “alpinekat”

Still room for improvement…
### FRIB: Cultural Impact

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<td>52,325</td>
</tr>
<tr>
<td>Cornell “Robotic Self Healing Chair”</td>
<td>937,129</td>
</tr>
</tbody>
</table>

as of 2 August 2010

Still room for improvement…

Katherine McAlpine
2007 graduate of MSU
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Production of Rare Isotopes at Rest: *Isotope Separation On Line* (ISOL)

Heavy nucleus in thick target

Projectile: Light nucleus

Extract rare isotopes from target (effusion or diffusion); ionize and accelerate to produce secondary beam
Production of Rare Isotopes in Flight: Particle Fragmentation

Projectile: heavy nucleus

Nucleus in thin target

Projectile fragment
Production of Rare Isotopes in Flight: Particle Fragmentation

Projectile: heavy nucleus

Nucleus in thin target

Rare isotope beam

projectile fragment

projectile fragment
A heavy-ion linac can also accelerate light ions needed for an ISOL facility.
<table>
<thead>
<tr>
<th>Component</th>
<th>Charge State at exit&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Beam Energy at exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECR Ion Source</td>
<td>20-40</td>
<td>4 keV/u</td>
</tr>
<tr>
<td>$q/A$ selection</td>
<td>33-34</td>
<td>12 keV/u</td>
</tr>
<tr>
<td>Multi-Harmonic Buncher</td>
<td>33-34</td>
<td>12 keV/u</td>
</tr>
<tr>
<td>Radio Frequency Quadrupole</td>
<td>33-34</td>
<td>0.3 MeV/u</td>
</tr>
<tr>
<td>SRF Linac</td>
<td>33-34</td>
<td>16.6 MeV/u</td>
</tr>
<tr>
<td>Charge Stripping Station</td>
<td>76-80</td>
<td>16.4 MeV/u</td>
</tr>
<tr>
<td>SRF Linac</td>
<td>76-80</td>
<td>208 MeV/u</td>
</tr>
<tr>
<td>Beam Delivery to Target</td>
<td>76-80</td>
<td>208 MeV/u</td>
</tr>
</tbody>
</table>

<sup>a</sup>for uranium case ($Z = 92$, $A = 238$)
ReA3 - MSU
- High-intensity EBIT as 1+ \(\rightarrow\) n+ charge breeder
- RT RFQ and SRF QWR cavities and cryomodules
- Energies 0.3 to 3 MeV/u

ReA12 - FRIB
- Energies 0.3 to 12 MeV/u
- **ReA3** - MSU
  - High-intensity EBIT as 1+ → n+ charge breeder
  - RT RFQ and SRF QWR cavities and cryomodules
  - Energies 0.3 to 3 MeV/u

- **ReA12** - FRIB
  - Energies 0.3 to 12 MeV/u
- **ReA3** - **MSU**
  - High-intensity EBIT as 1+ → n+ charge breeder
  - RT RFQ and SRF QWR cavities and cryomodules
  - Energies 0.3 to 3 MeV/u

- **ReA12** - FRIB
  - Energies 0.3 to 12 MeV/u

---

**FRIB Secondary Beam Radioactive Ion Reaccelerator**

- **ReA3**
  - High-intensity EBIT as 1+ → n+ charge breeder
  - RT RFQ and SRF QWR cavities and cryomodules
  - Energies 0.3 to 3 MeV/u

- **ReA12** - FRIB
  - Energies 0.3 to 12 MeV/u
Black – production in target (ISOL)
Magenta – in-flight (particle fragmentation)
Domain of FRIB Research

[Graph showing the domain of FRIB research in the proton number vs. neutron number plane with regions labeled rp-process and r-process.]

FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy
Office of Science
Michigan State University

W. Hartung, 3 August 2010, Slide 19
High beam rates are needed to do the science

Next-generation high-power (>100 kW) RIB facilities are the key

**FRIB** 400 kW, 200 MeV/u uranium

Gain factors of 10-10000 over operational facilities

Reach to driplines

Make r-process nuclei

Proton dripline

Neutron dripline

W. Hartung, 3 August 2010, Slide 20
The Four Themes of Research at FRIB

Properties of nuclei (nuclear structure)
- To develop a predictive model of nuclei and their interactions
- Study of many-body quantum physics: part of mesoscopic science – quantum dots, clusters of atoms, etc.

Nuclear processes in the universe
- Chemical history of the universe, (explosive) nucleo-synthesis
- Properties of neutron stars, EOS of asymmetric nuclear matter

Tests of fundamental symmetries
- Effects of symmetry violations are amplified in certain nuclei

Societal applications and benefits
- Bio-medicine, energy, material sciences, national security
What is the origin of the elements in the cosmos?
- Synthesis of neutron-rich nuclei heavier than iron: r-process
- Gamma-ray emitters in supernovae

What are the nuclear reactions that drive stellar explosions?
- Synthesis of proton-rich nuclei: rp-process
- Weak interactions in supernovae

What is the nature of neutron stars and dense nuclear matter?
- Nuclear processes in the crusts of neutron stars
- Symmetry energy term of equation of state of nuclear matter
Applications of Rare Isotopes

- Cross sections for evaluation of new nuclear technologies such as transmutation of nuclear waste
- New radioisotopes for medicine – targeted cancer therapy, diagnostics
- Tracers
- Stockpile stewardship – allow measurements of necessary cross sections to insure the reliability of simulations
Original FRIB Location on MSU Campus

Green – existing

Blue - new

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U.S. Department of Energy Office of Science
Michigan State University

W. Hartung, 3 August 2010, Slide 25
Two tunnels: linac tunnel and RF/service tunnel
Problem: Conventional Construction Cost higher than anticipated

How to reduce the cost of conventional facilities?

Is there a linac layout that allows for lower cost?

Are you trying to redesign a FRIB?

W. Hartung, 3 August 2010, Slide 27
Double-folded Linac “Operation Paperclip”

Physically compact layout; minimize tunnel size; one tunnel for 3 linac segments

 Are you trying to redesign a FRIB?

FRIB
Facility for Rare Isotope Beams
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W. Hartung, 3 August 2010, Slide 28
Reduce cost by minimizing tunnel level footprint

- Underground tunnel area is minimized by using a common tunnel for all three segments
- RF/service area on ground level
- Combines utility, front end and cryoplant building
- Minimizes campus utility disruption

Minimum cost for conventional construction
On Site Double-folded Layout
- In-flight separation of rare isotopes with high acceptance and high resolution

- 3-stage separation
  - Provide purest isotopes
  - Beam purity critical to new discoveries
Minimal perturbation of the experimental area when transitioning from NSCL to FRIB operations
Resonators: $\lambda/4$ and $\lambda/2$

- **Superconducting $\lambda/4$ resonators:** in use for ion acceleration for many years. Examples: Argonne, JAERI, Legnaro, TRIUMF…
  - Long experience with common vacuum systems
  - Limited experience with separated vacuum systems

- **Superconducting $\lambda/2$ resonators:** limited experience so far
  - First prototype developed at Argonne by J. R. Delayen, C. L. Bohn, and C. T. Roche, c. 1990
  - First experience with operation: SARAF/SOREQ (Israel)
## RF Parameters for FRIB Resonators

<table>
<thead>
<tr>
<th>Type</th>
<th>$\lambda/4$</th>
<th>$\lambda/4$</th>
<th>$\lambda/2$</th>
<th>$\lambda/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{opt}$</td>
<td>0.041</td>
<td>0.085</td>
<td>0.29</td>
<td>0.53</td>
</tr>
<tr>
<td>$f$ (MHz)</td>
<td>80.5</td>
<td>80.5</td>
<td>322.0</td>
<td>322.0</td>
</tr>
<tr>
<td>$V_a$ (MV)</td>
<td>0.81</td>
<td>1.62</td>
<td>1.90</td>
<td>3.70</td>
</tr>
<tr>
<td>$E_p$ (MV/m)</td>
<td>30.0</td>
<td>31.5</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>$B_p$ (mT)</td>
<td>53</td>
<td>71</td>
<td>75</td>
<td>77</td>
</tr>
<tr>
<td>$R/Q$ (Ω)</td>
<td>433</td>
<td>408</td>
<td>202</td>
<td>219</td>
</tr>
<tr>
<td>$G$ (Ω)</td>
<td>15</td>
<td>18</td>
<td>59</td>
<td>101</td>
</tr>
<tr>
<td>Design $Q_0$</td>
<td>$5\times10^8$</td>
<td>$5\times10^8$</td>
<td>$6.1\times10^9$</td>
<td>$1.0\times10^{10}$</td>
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<tr>
<td>Aperture (mm)</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>4.5</td>
<td>4.5</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Maximum $\phi_s$</td>
<td>$-26.5^\circ$</td>
<td>$-23.5^\circ$</td>
<td>$-32.0^\circ$</td>
<td>$-25.0^\circ$</td>
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</table>
Component Counts for FRIB Linac

<table>
<thead>
<tr>
<th>Type</th>
<th>$\lambda/4$</th>
<th>$\lambda/4$</th>
<th>$\lambda/2$</th>
<th>$\lambda/2$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{\text{opt}}$</td>
<td>0.041</td>
<td>0.085</td>
<td>0.29</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td>Resonators</td>
<td>16</td>
<td>96</td>
<td>78</td>
<td>144</td>
<td>344</td>
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<tr>
<td></td>
<td>[0]</td>
<td>[2]</td>
<td>[4]</td>
<td>[4]</td>
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<tr>
<td>Solenoids</td>
<td>16</td>
<td>36</td>
<td>13</td>
<td>18</td>
<td>87</td>
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<tr>
<td></td>
<td>[0]</td>
<td>[0]</td>
<td>[2]</td>
<td>[2]</td>
<td></td>
</tr>
<tr>
<td>Cryomodules</td>
<td>4</td>
<td>12</td>
<td>13</td>
<td>18</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>[0]</td>
<td>[1]</td>
<td>[2]</td>
<td>[2]</td>
<td></td>
</tr>
</tbody>
</table>

$\# = \text{accelerating cryomodules} \quad [\#] = \text{matching cryomodules}$

Plus 5 accelerating cryomodules and 4 matching cryomodules for Re-accelerator (ReA3 + ReA12)
## Resonator Development

<table>
<thead>
<tr>
<th>Type</th>
<th>$\lambda/4$</th>
<th>$\lambda/4$</th>
<th>$\lambda/2$</th>
<th>$\lambda/2$</th>
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<td>0.29</td>
<td>0.53</td>
</tr>
</tbody>
</table>

### 1st generation

<table>
<thead>
<tr>
<th>Test</th>
<th>1st generation</th>
<th>2nd generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabricated</td>
<td>1 cavity</td>
<td>9 cavities</td>
</tr>
<tr>
<td>Dewar test</td>
<td>1 cavity</td>
<td>8 cavities</td>
</tr>
<tr>
<td>Systems test</td>
<td>Low-$\beta$ test module (RIA)</td>
<td>7 cavities in progress (ReA3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 cavities planned (ReA3)</td>
</tr>
</tbody>
</table>

### 2nd generation

<table>
<thead>
<tr>
<th>Test</th>
<th>1st generation</th>
<th>2nd generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dewar test</td>
<td>in progress</td>
<td>2 cavities planned (FRIB)</td>
</tr>
<tr>
<td>Systems test</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$\beta = 0.041$ Resonators

Legnaro-style damper
TRIUMF-style tuning plate

Resonator with helium vessel, tuning plate, and bottom flange

Stiffening elements

Prep for Dewar
$\beta = 0.041$ Resonators

Dewar Testing

Bottom flange redesign: add reservoir for liquid He cooling
$\beta = 0.041$ Resonators

Dewar Testing

Production cavities at 4.3 K without bottom flange cooling
Production cavities: Final Dewar test at 4.3 K with bottom flange cooling for last 6

Total of 7 certified resonators
$\beta = 0.085$ Resonators
RIA prototype

Sub-assemblies

Completed resonator

Prep for Dewar
\[ \beta = 0.085 \text{ Resonators for ReA3} \]

Sub-assemblies

Completed cavity

Stiffening elements
$\beta = 0.085$ Resonators

Dewar Tests

Dewar tests:

RIA prototype at 4.2 K: meets FRIB goal, no margin

Second ReA3 resonator at 4.3 K: margin in $Q$ and field

Other ReA3 resonators: testing in progress
β = 0.53 Resonators
Niobium Prototype

Spiral2-style rinse ports with plungers

Nb parts

Completed resonator
\( \beta = 0.53 \) Resonators

Niobium Prototype

Preparations for Dewar test

Etching

Rinsing

Assembly onto insert
$\beta = 0.53$ Resonators
Niobium Prototype

Dewar test: no plungers no vessel
No MP observed; limited by “quench”
Plan to repeat with plungers
Systems Tests
$\beta = 0.041$ Resonators

Cold mass:
One $\beta = 0.041$ $\lambda/4$ resonator, 2 solenoids

77 K shield, MLI, vacuum vessel

First cryomodule (rebuncher) for ReA3: under test
Systems Test: ReA3 Rebuncher
\[ \beta = 0.041 \text{ Resonator} \]

- Measured static heat leak = 8 W ± 1.2 W (predicted value = 6 W)
- Reached \( E_p = 36 \text{ MV/m} \) (FRIB goal: \( E_p = 30 \text{ MV/m} \))
- RF coupler power is about 500 W for \( E_p = 36 \text{ MV/m} \)
- Tuner operates over full range: 28 kHz
- Have operated the solenoids at fields required for ReA3
- Measurement of \( Q_0 \) in progress (plan to measure He gas flow for calorimetric determination of \( Q_0 \))
- Measurements in progress, including microphonics studies and amplitude and phase control
Second cryomodule for ReA3: cold mass complete

Systems Test

$\beta = 0.041$ Resonators
Systems Test
$\beta = 0.041$ Resonators

Second cryomodule for ReA3: assembly and installation

Top plate, thermal shield, MLI

Vacuum vessel, move, installation
Resonators and Cryomodules: Issues of Interest

- Operation of resonators in proximity to 9 T solenoid
- Hydrogen degas (600 to 800°C) is not presently used; to be evaluated
- 120°C bake is not presently used; to be further evaluated
- Buffered chemical polishing: using chilled acid. Additional cooling of cavity wall being investigated
- Multipacting in $\lambda/2$ resonators is of concern (at plungers in rinse ports, in particular). Calculations being done at SLAC Nat’l Accelerator Lab; experimental results being acquired.
- Operating temperature for resonators
  - Original plan: 2 K for $\lambda/2$ resonators and 4.5 K for $\lambda/4$ resonators
  - Under consideration: 2 K for all resonators
Magnetic Shielding

- Must shield the magnetostatic field of the solenoid to avoid degradation of resonator performance

1. Solenoid on, resonator cold: field must not exceed resonator $H_c$
2. Solenoid off, resonator warm: potential to trap residual field and Earth’s field upon cool-down
3. Solenoid on, unintentional warm-up of resonator: potential to trap stray field of solenoid

- Demagnetization may be required after solenoid operation to reduce residual field (Case 2)
- Warm-up (above $T_c$) may be required if stray field becomes trapped (Case 3)
Superconducting solenoids are in proximity to resonators in all FRIB accelerating cryomodules.
Magnetic Shielding

Solution A

Tested in Dewar for RIA—shielding effective

Tested in RIA low-beta test module—shielding effective

Used for first ReA3 module

Second ReA3 module: field too high for Meissner shield
Magnetic Shielding

Solution B

- Tested in Dewar for ReA3—not tried demagnetisation yet
- Used for second ReA3 module
- Planned for third ReA3 module
- Possible solution for FRIB
Magnetic Shielding

Solution C

Used for ISAC-II at TRIUMF
Planned for FRIB 2-cavity test cryomodule
Possible solution for FRIB, potential cost reduction
Magnetic Shielding

- Have gained experience with Dewar tests and cryomodule tests (Solutions A and B)
- Additional experience to be gained from ReA3 and FRIB 2-cavity module (Solutions B and C)
- Solution C: usefulness of secondary Meissner shield under consideration
- Experience with ReA3 and FRIB R & D will provide the basis for the final design of FRIB cryomodules
Operating Temperature

Dewar tests
\( \beta = 0.041 \) resonator

- ReA3
- FRIB

- 4.6 K
- 4.2 K
- 2.0 K

\( Q_0 \) vs. \( E_p \) [MV/m]
Operating Temperature

Dewar tests
\( \beta = 0.041 \) resonator

Low field:
4.5 K preferred

High field:
2.0 K could provide an advantage

\( E_p \) [MV/m]

\( Q_0 \)

ReA3 FRIB
3180210-013
Operating Temperature

Dewar tests
\( \beta = 0.085 \) ReA3 resonator
Dewar tests

$\beta = 0.085 \text{ ReA3 resonator}$

2 K provides some advantage at FRIB field
RF Bandwidth, RF Power, Coupling Strength

- Strength of input RF coupling ($Q_{ext}$) determines the RF bandwidth and the RF power required (must be ≥ beam power)
- Need to make the bandwidth large enough to allow the RF amplitude and phase controller to compensate for frequency disturbances (microphonics, etc)
- Use stiffening and frictional dampers ($\lambda/4$ resonators) to reduce amplitude of frequency disturbances
- Need to minimise pressure fluctuations in cryogenic system
- Have gained experience via cryomodule testing and vibration measurements
RF Bandwidth, RF Power, Coupling Strength

|                      | RF couplers & RF power | RF bandwidth $P_g/P_b$ | ≥ 30 Hz  
|----------------------|------------------------|------------------------|------------
|                      |                        | ≥ 2.0                  |            |
| Resonators           | $|df/dP|$               | < 2 Hz/torr            |            |
| Cryogenic system     | Pressure stability (fast fluctuations) | 1 torr peak-to-peak |            |
| Tunnel               | RMS displacement       | ≤ 40 nm                |            |

- Specs to be refined on the basis of further experience with ReA3 and FRIB R & D
- Vibrations from the cryoplant must not produce excessive frequency disturbances for the resonators; vibration measurements at NSCL and SNS indicate that current facility layout is viable; additional measurements planned at CEBAF
RF Couplers: $\lambda/4$ Resonators

- RF couplers for the $\lambda/4$ resonators have been developed for ReA3
- Gaining experience with conditioning and operation via ReA3
- Useful feedback obtained during April 2010 review
- Experience to be used to finalise design of $\lambda/4$ couplers for FRIB
RF Couplers: $\lambda/2$ Resonators

- RF couplers for the $\lambda/2$ resonators have been designed, with assistance from group at SLAC; modification of RIA coupler, which is a modification of SNS coupler.
- Prototypes are being procured.
- RF conditioning technique follows SNS method.
80.5 MHz $\beta = 0.041$

- 4.5 K Cryogenic Circuit
- $\lambda/4$ Cavity
- Total QTY = 4

- 40 K Thermal Shield
- 9 T solenoid Magnet
- Vacuum Vessel
- Titanium Alignment Rails
- FPC/Tuner

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

W. Hartung, 3 August 2010, Slide 73
80.5 MHz $\beta = 0.085$

- 4.5 K Cryogenic Circuit
- $\lambda/4$ Cavity
- 9 T solenoid Magnet
- FPC/Tuner
- Vacuum Vessel
- Titanium Alignment Rails
- Total QTY = 12

40 K Thermal Shield

W. Hartung, 3 August 2010, Slide 74
322 MHz $\beta = 0.29$.

- 2 K Cryogenic Circuit
- 40 K Thermal Shield
- Vacuum Vessel
- Titanium Alignment Rails
- $\frac{\lambda}{2}$ Cavity
- 9 T solenoid Magnet & 4.5 K Circuit
- Total QTY = 13
Total QTY = 18

- 2 K Cryogenic Circuit
- 40 K Thermal Shield
- Vacuum Vessel
- Titanium Alignment Rails
- FPC
- 9 T solenoid Magnet & 4.5 K Circuit
- Tuner

W. Hartung, 3 August 2010, Slide 76
Summary: FRIB Project

- FRIB will allow major advances in nuclear science and nuclear astrophysics
  - Significant opportunities for the tests of fundamental symmetries
  - Potential for important societal applications
  - Campus-based location offers important educational and collaboration benefits

- 200 MeV/u, 400 kW driver linac
- Experimental capability for fast, stopped and reaccelerated beams
- Attractive upgrade options make the facility viable far beyond 2030
Summary: FRIB Resonators

- $\beta = 0.085$ and $\beta = 0.29$ resonators prototyped for RIA
- $\beta = 0.041$ and $\beta = 0.085$ resonators and cryomodules being produced for ReA3; experience benefits FRIB
- $\beta = 0.53$ resonator developed for FRIB; tests on Nb prototype in progress
- Statistics being accumulated on cavity performance to provide better basis for design parameters (impacts cryoplant and RF power requirements)
- Plan to gather more experience to provide better basis for operating temperature and cavity preparation steps. Get experience from:
  - ReA3 resonators and cryomodule
  - One FRIB test cryomodule (2 resonators, 1 solenoid)
  - Two FRIB first article cryomodules (8 resonators, 1 solenoid each)
People

- **MSU Staff**

- **MSU Graduate Students**
  - M. Hodek, J. Holzbauer

- **Collaborators**
  - G. Ciovati, P. Kneisel, et al. (CEBAF)
  - A. Facco et al. (INFN Legnaro)
  - E. Zaplatin (Juelich)

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*Facility for Rare Isotope Beams*

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Michigan State University

W. Hartung, 3 August 2010, Slide 79